AAMQS: A non-linear QCD analysis of new HERA data at small-x including heavy quarks

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OUTLINE

⇒ Motivation. Dipole model of DIS

⇒ Running coupling corrections to BK evolution

⇒ Fits to DIS inclusive structure function at small-x

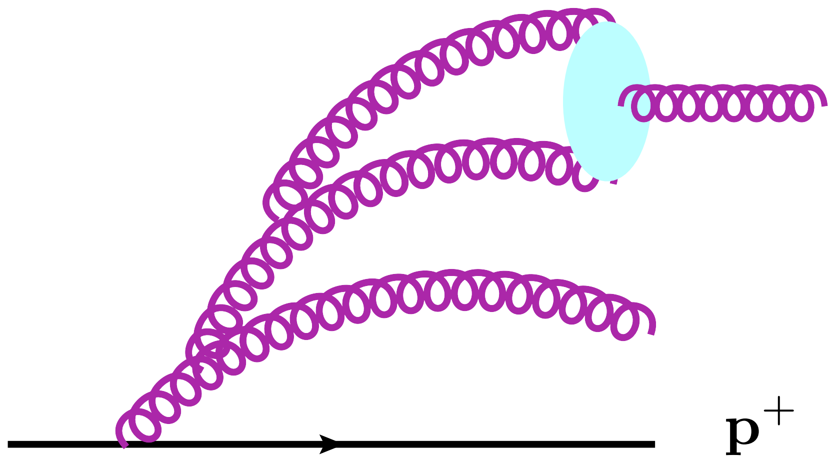
⇒ Inclusion of heavy quarks

⇒ Conclusions/Outlook

Based on:

- JLA, N. Armesto, J.G. Milhano P. Quiroga and C. Salgado (arXiv 1012.4408 [hep-ph])
- JLA, N. Armesto, J.G. Milhano and C. Salgado (arXiv 1209.1112 [hep-ph])
- JLA PRL99:262301
- JLA and Y. Kovchegov PRD75:125021

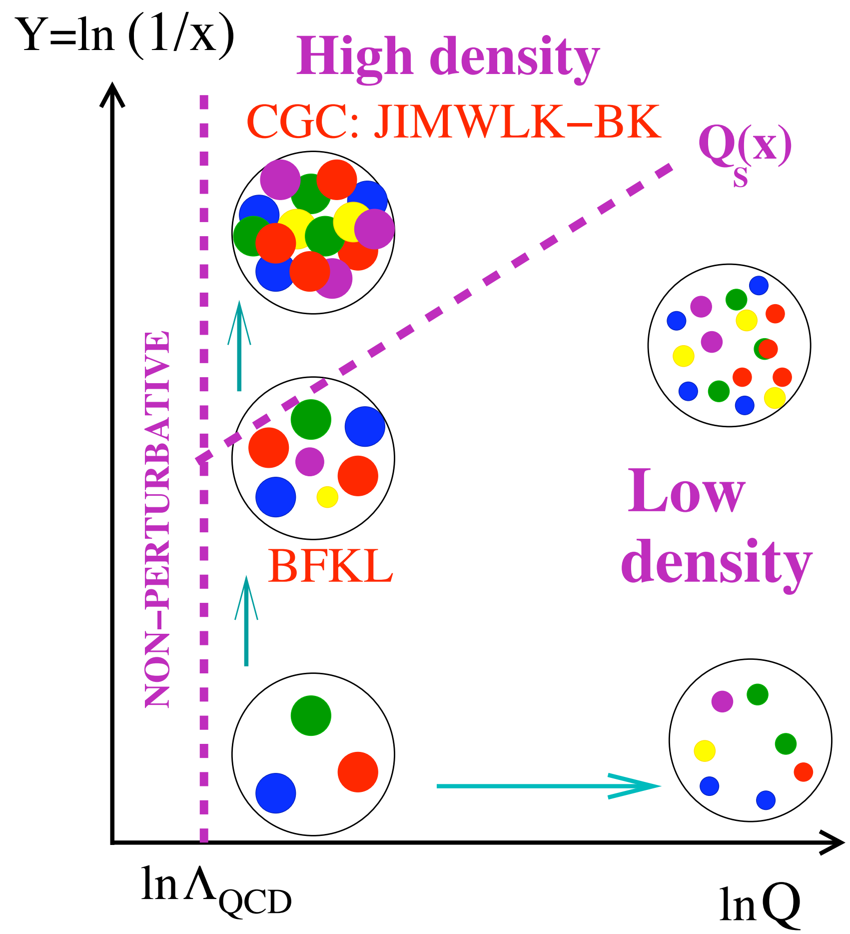
⇒ **Saturation:** At small Bjorken-x the hadron wave function gets dense and non-linear processes become a relevant dynamical ingredient



"BK-JIMWLK"

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^{\mathbf{2}}$$

Non-linear *recombination* corrections are demanded by UNITARITY

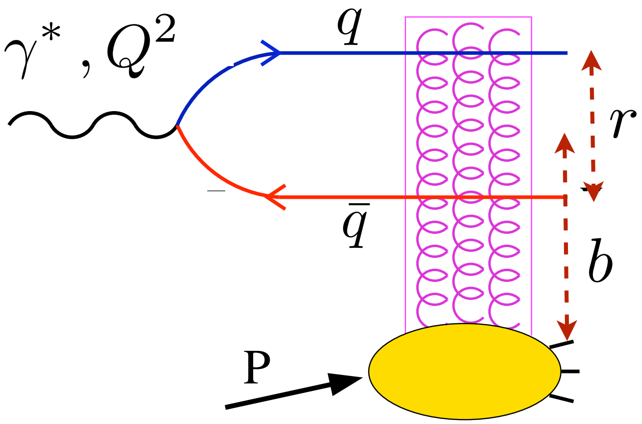


⇒ To what extent are such effects present in available e+p data?

Dipole model of DIS

⇒ Dipole models including saturation describe a large amount of HERA data (inclusive and longitudinal structure functions, diffraction, DVCS, VM, geometric scaling..).

⇒ They provide insight in the region "forbidden" to DGLAP (Q^2<2 GeV^2).

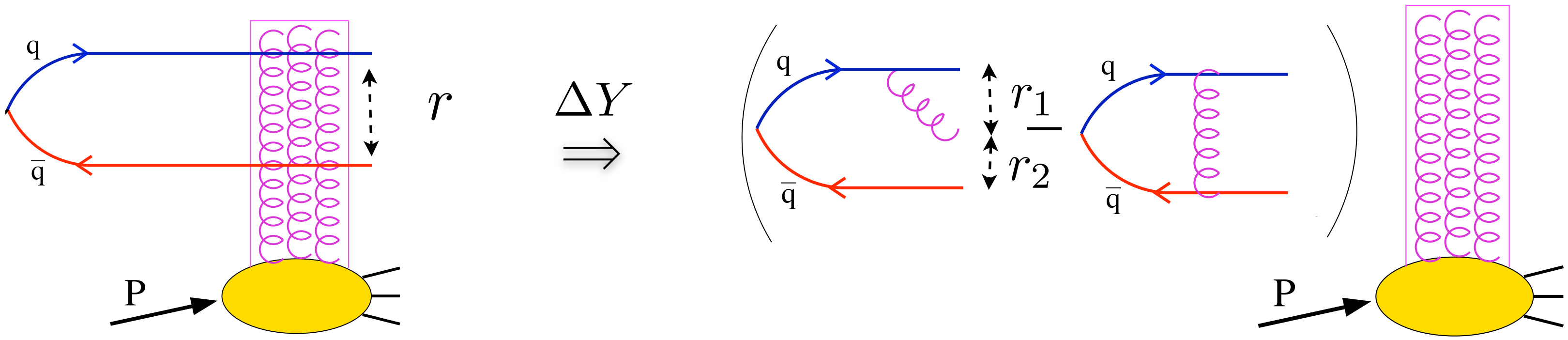


$$\sigma_{T,L}^{\gamma^* P}(x, Q^2) = \int_0^1 dz \int d^2\mathbf{r} \left| \Psi_{T,L}^{\gamma^* \to q\bar{q}}(z, Q, r) \right|^2 \sigma^{dip}(x, r)$$

$$\sigma^{dip}(x, r) = 2 \int d^2 b \mathcal{N}(x, b, r) \rightarrow$$

Dipole cross section.
Strong interactions and x-dependence are here

⇒ pQCD tools: The non-linear Balitsky-Kovchegov eqn. describes the small-x evolution of the dipole scattering amplitude at leading order in $\alpha_s \ln(1/x)$

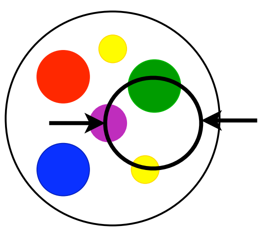


$$\frac{\partial \mathcal{N}(x,r)}{\partial \ln(x_0/x)} = \int d^2r_1\, K^{LO}(\mathbf{r},\mathbf{r_1},\mathbf{r_2})\,[\mathcal{N}(x,r_1)+\mathcal{N}(x,r_2)-\mathcal{N}(x,r)-\mathcal{N}(x,r_1)\mathcal{N}(x,r_2)]$$

The LL kernel: $K^{L0}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \dfrac{\alpha_s\, N_c}{2\,\pi^2}\,\dfrac{r^2}{r_1^2\, r_2^2}$

Non-linear term

⇒ However, at LL accuracy (fixed coupling) the BK equation is not compatible with data



$$\begin{cases} Q_s^2(Y) = Q_0^2\, \exp \lambda Y \\ \lambda = \dfrac{d \ln Q_s^2(Y)}{dY} \end{cases}$$

Fits to HERA and RHIC data	LL-BK (fixed coupling)
$\lambda \sim 0.2 \div 0.3$	$\lambda^{LL} \sim 4.8\, \alpha_s$

Running coupling corrections (Kovchegov-Weigert, Balitsky, Gardi et al)

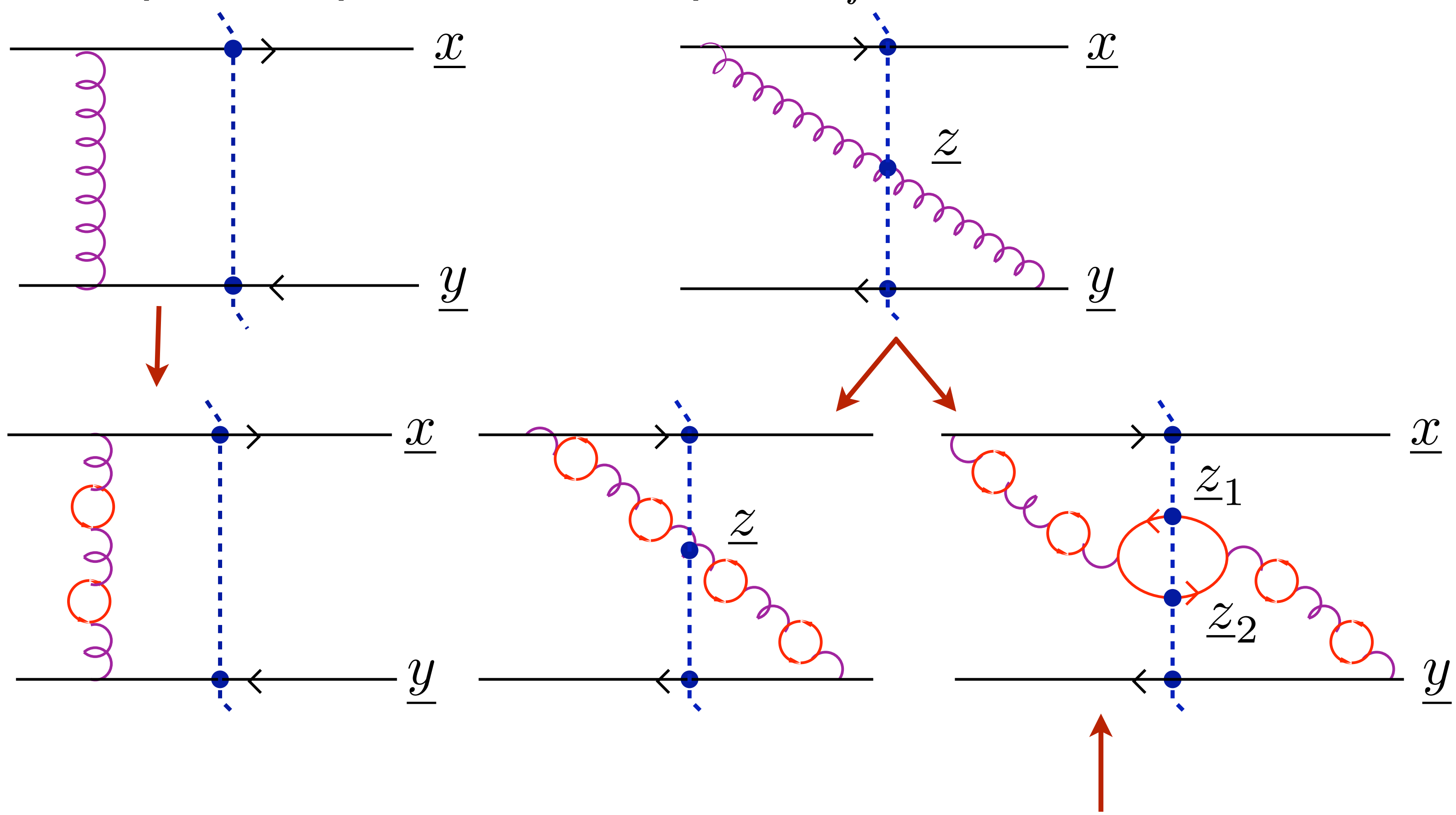
Strategy: resummation of quark loops to all orders, plus $N_f \longrightarrow -6\pi\beta$

$\Rightarrow$ Leading log
(fixed coupling)

$\Rightarrow$ All orders in $\alpha_s N_f$

$N_f \longrightarrow -6\pi\beta$

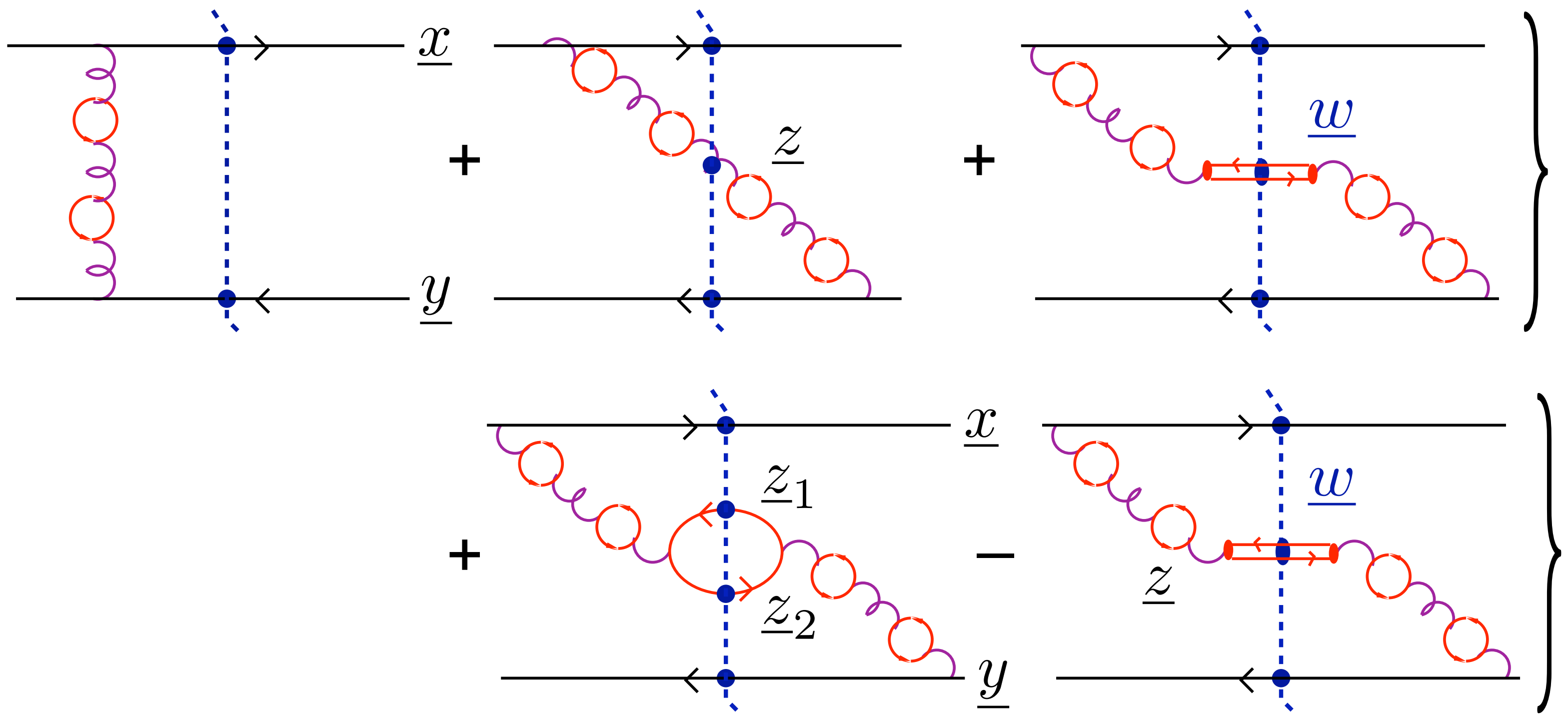
(running coupling)



New physical channels: quark-antiquark pairs in the final state.
They contain UV divergencies that contribute to the running of the coupling

Complete in $\alpha_s N_f$ Evolution JLA-Kovchegov PRD75 125021 (07).

$$\frac{\partial S}{\partial Y} = \mathcal{R}\left[S\right] - \mathcal{S}\left[S\right]$$



$\mathcal{R}[S]$

UV-divergent

Contributes to the running of the coupling

$\mathcal{S}[S]$

UV finite.

⇒ ***Running*** term: $\mathcal{R}\left[S\right] = \int d^2 z\, \tilde{K}(\underline{r}, \underline{r}_1, \underline{r}_2) \left[S(\underline{x}, \underline{z}) S(\underline{z}, \underline{y}) - S(\underline{x}, \underline{y})\right]$

⇒ ***Subtraction*** term: $\mathcal{S}\left[S\right] = \int d^2 z_1 d^2 z_2\, K_{sub}(\underline{x}, \underline{y}, \underline{z}_1, \underline{z}_2) \left[S(\underline{x}, \underline{w}) S(\underline{w}, \underline{y}) - S(\underline{x}, \underline{z}_1) S(\underline{z}_2, \underline{y})\right]$

Two different separation schemes: Balitsky's (BAL) and Kovchegov-Weigert's (KW)

Fixed vs Running

⇒ The running of the coupling reduces the speed of the evolution down to values compatible with experimental data (JLA PRL 99 262301 (07)):

$$\frac{\partial S}{\partial Y} = \mathcal{R}\left[S\right] - \mathcal{S}\left[S\right]$$

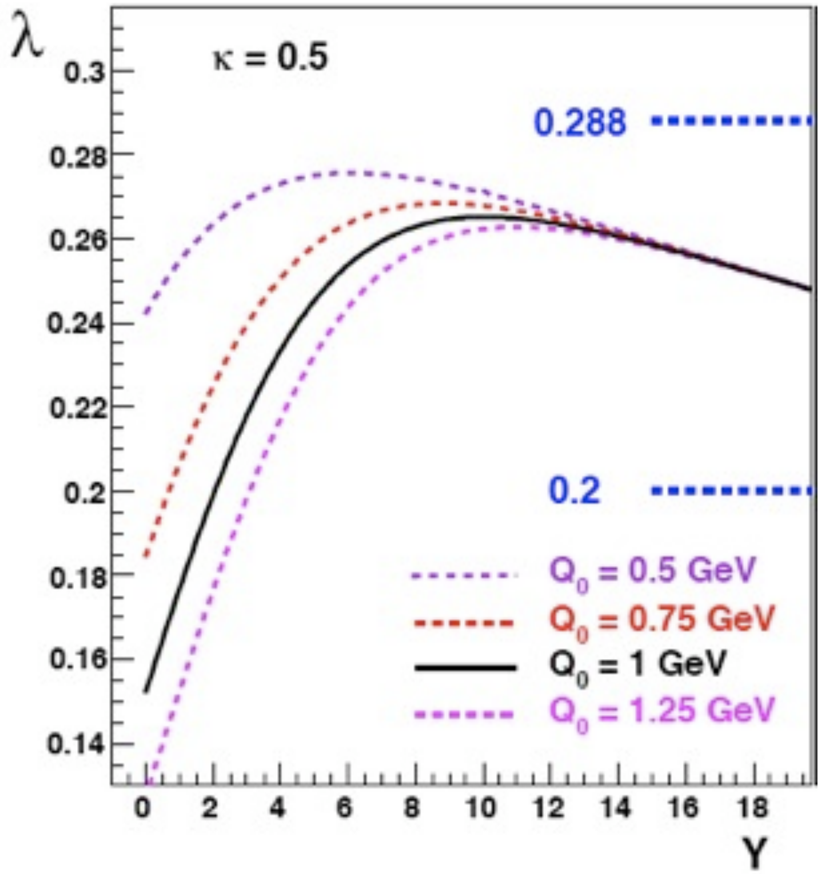
$$\lambda = \frac{d \ln Q_s^2(Y)}{dY}$$

LL evolution:

$$\lambda^{LL} \approx 4.8\,\alpha_s$$

DIS data:

$$\lambda^{DIS} \approx 0.288$$



⇒ Fits to inclusive DIS e+p structure functions & reduced x-section

$$F_2(x,Q^2) = \frac{Q^2}{4\,\pi^2\,\alpha_{em}}\,(\sigma_T + \sigma_L) \qquad \sigma_r(y,x,Q^2) = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2),$$

⇒ x-dependence: translational invariant (no b-dependence) running coupling BK using Balitsky's prescription

$$\frac{\partial \mathcal{N}(x,r)}{\partial \, \ln(x_0/x)} = \int d^2 r_1 \, K^{Bal}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) \left[\mathcal{N}(x,r_1) + \mathcal{N}(x,r_2) - \mathcal{N}(x,r) - \mathcal{N}(x,r_1)\mathcal{N}(x,r_2)\right]$$

$$K^{Bal}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{N_c\,\alpha_s(r^2)}{2\,\pi^2}\left[\frac{r^2}{r_1^2\,r_2^2} + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

⇒ Regularization of the coupling: We freeze to a constant, α_{fr}=0.7 in the IR:

$$\alpha_s(r^2) = \frac{12\,\pi}{(11\,N_c - 2\,N_f)\ln\left(\frac{4\,C^2}{r^2\,\Lambda_{QCD}}\right)} \qquad \text{for } r < r_{fr}, \ \text{with } \alpha_s(r_{fr}^2) \equiv \alpha_{fr} = 0.7$$

$$\alpha_s(r^2) = \alpha_{fr} = 0.7 \qquad \text{for } r > r_{fr} \qquad\qquad \Lambda_{QCD} = 0.241\,\text{GeV}$$

⇒ Initial Conditions. Inspired in the GBW and MV models:

A) $$\mathcal{N}^{GBW}(r, x_0 = 10^{-2}) = 1 - \exp\left[-\left(\frac{r^2\, Q_{s0}^2}{4}\right)^{\gamma}\right]$$

B) $$\mathcal{N}^{MV}(r, x_0 = 10^{-2}) = 1 - \exp\left[-\left(\frac{r^2\, Q_{s0}^2}{4}\right)^{\gamma} \ln\left(\frac{1}{r\,\Lambda_{QCD}}\right)\right]$$

C) "scaling" $\mathcal{N}(r, Y \gg 1) \to \mathcal{N}^{scal}(\tau = r\, Q_s(Y)).$ $\quad r\, Q_s(Y) \to r\, Q_{s0}$

Free parameters: proton saturation scale at $x_0=10^{-2}$, Q_{s0}^2, and anomalous dimension, γ

⇒ Overall normalization: $2\int d\mathbf{b} \to \sigma_0$

kinematic shift: $\tilde{x} = x\left(1 + \frac{4\, m_f^2}{Q^2}\right)$

⇒ 3 (4) free parameters: Normalization, σ_0 , initial saturation scale, Q_{s0}^2

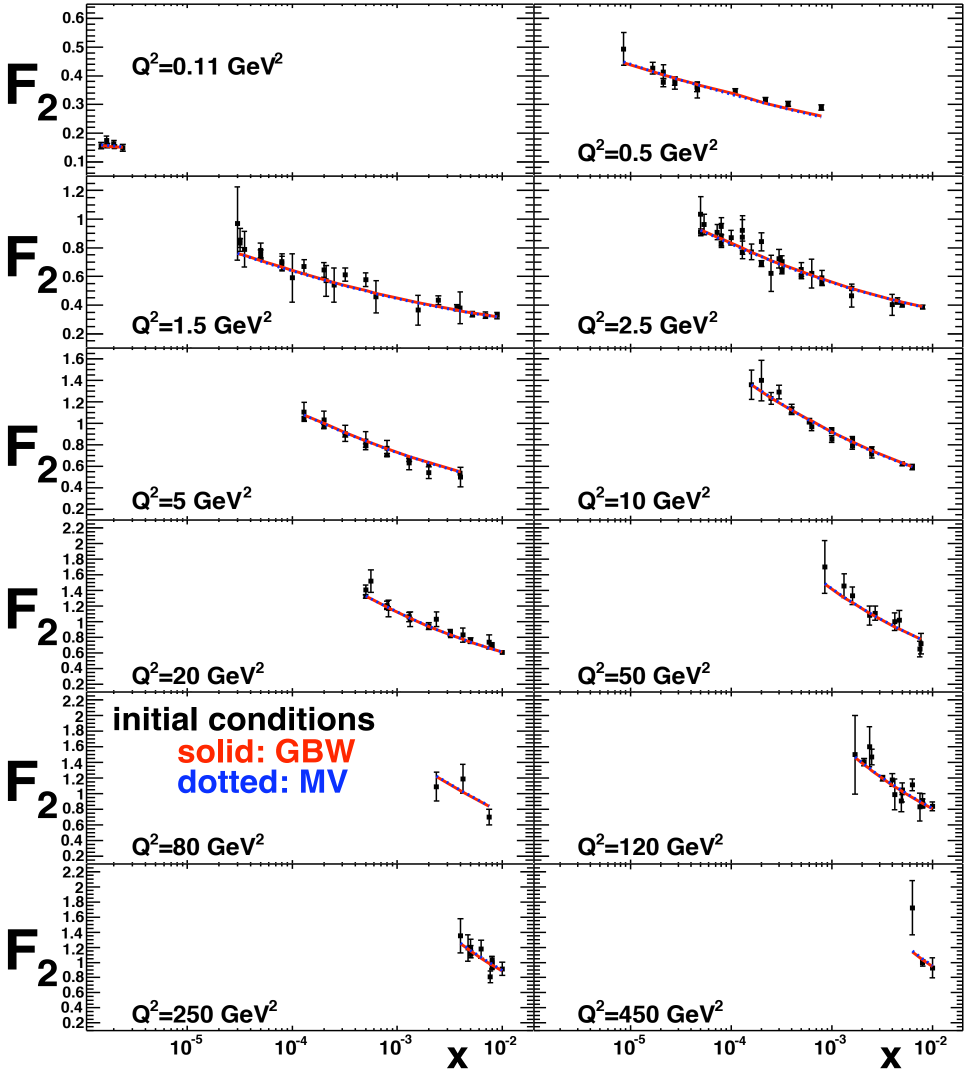
IR parameter, C^2 (anomalous dimension of the i.c. γ)

⇒ Experimental data: New ZEUS+H1 combined analysis (HERA), NMC (CERN-SPS) and E665 (Fermilab) coll.

$$x \leq 10^{-2} \quad 0.045 < Q^2 < 50\,\mathrm{GeV}^2$$

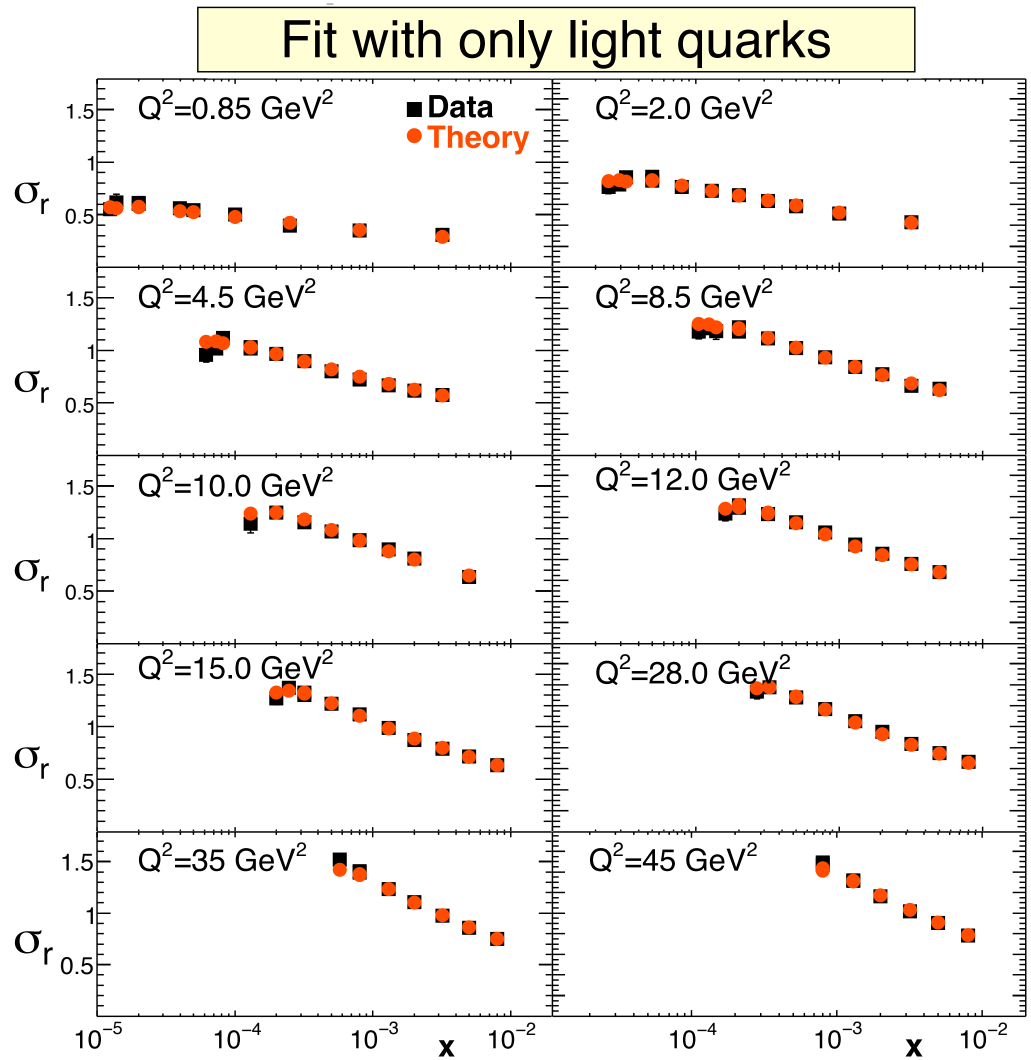
⇒ Fit results

Fits to “OLD” HERA data



JLA, N. Armesto, J.G. Milhano, C. Salgado
Phys.Rev.D80:034031,2009;

Combined H1 + ZEUS data



JLA, N. Armesto, J.G. Milhano, P Quiroga and C. Salgado arXiv 1012.4408 [hep-ph]

$\Rightarrow$ Fit results

- Fits parameters are stable w.r.t to the fits to older data

	fit	$\frac{\chi^2}{d.o.f}$	Q^2_{s0}	σ_0	γ	C	m_l^2
	GBW						
a	$\alpha_{fr} = 0.7$	1.226	0.241	32.357	0.971	2.46	fixed
a’	$\alpha_{fr} = 0.7\ (\Lambda_{m_\tau})$	1.235	0.240	32.569	0.959	2.507	fixed
b	$\alpha_{fr} = 0.7$	1.264	0.2633	30.325	0.968	2.246	1.74E-2
c	$\alpha_{fr} = 1$	1.279	0.254	31.906	0.981	2.378	fixed
c’	$\alpha_{fr} = 1\ (\Lambda_{m_\tau})$	1.244	0.2329	33.608	0.9612	2.451	fixed
d	$\alpha_{fr} = 1$	1.248	0.239	33.761	0.980	2.656	2.212E-2
	MV						
e	$\alpha_{fr} = 0.7$	1.171	0.165	32.895	1.135	2.52	fixed
f	$\alpha_{fr} = 0.7$	1.161	0.164	32.324	1.123	2.48	1.823E-2
g	$\alpha_{fr} = 1$	1.140	0.1557	33.696	1.113	2.56	fixed
h	$\alpha_{fr} = 1$	1.117	0.1597	33.105	1.118	2.47	1.845E-2
h’	$\alpha_{fr} = 1\ (\Lambda_{m_\tau})$	1.104	0.168	30.265	1.119	1.715	1.463E-2

NOTE: Statistical and systematic errors added in quadrature

⇒ Including heavy quarks

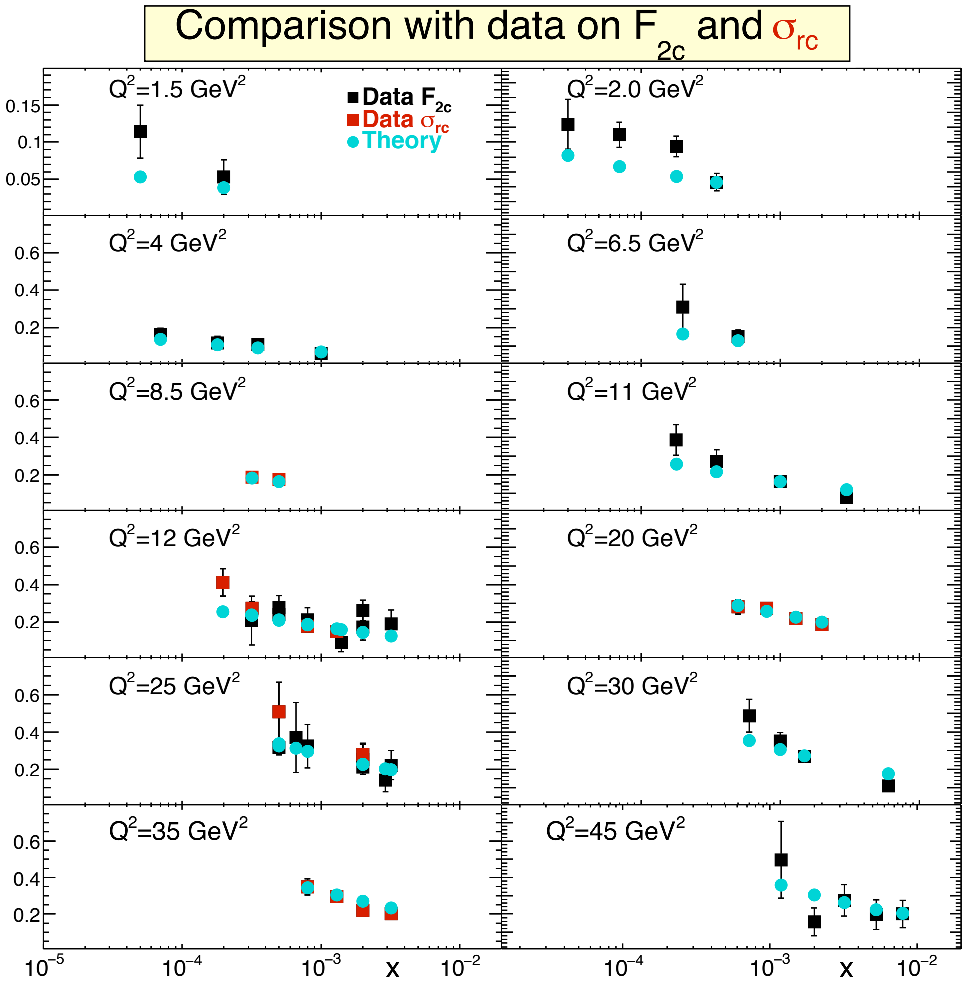
- Extend the sum to heavy flavors (b and c) in the dipole model
- Allow for different parameters for the heavy quark contribution and initial conditions

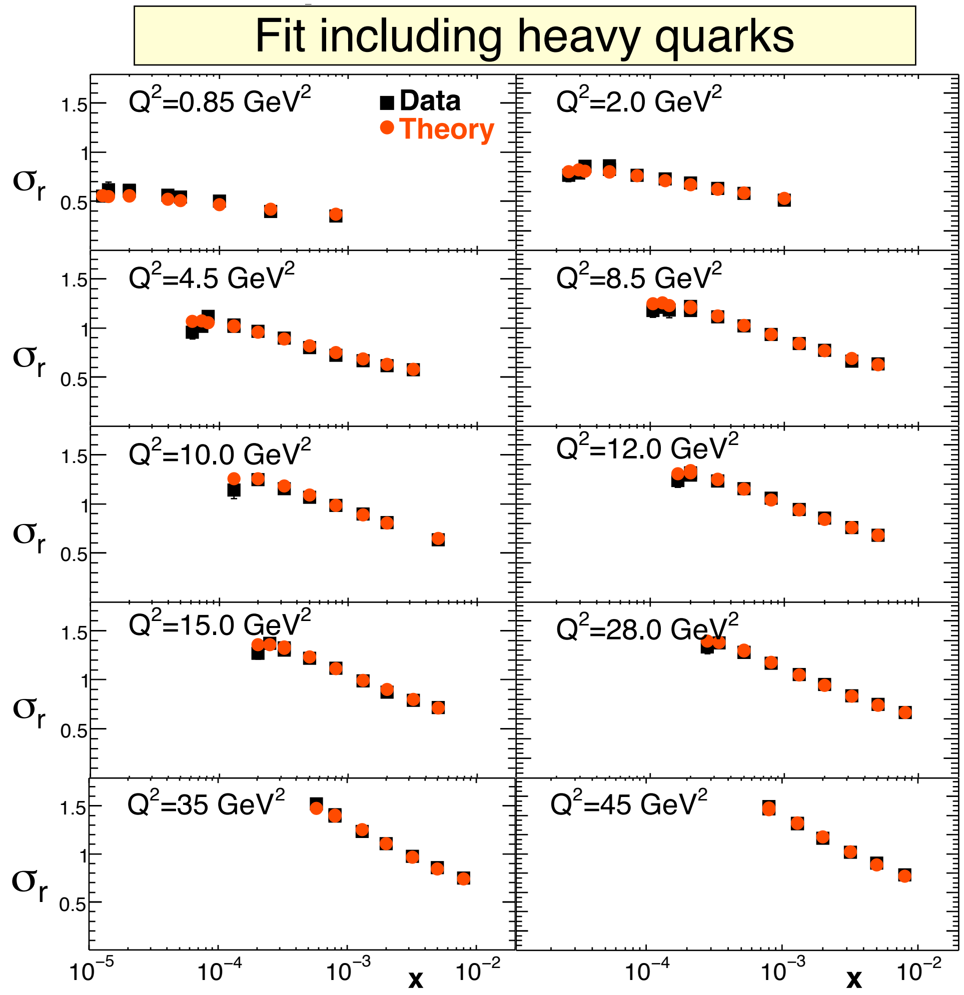
$$\sigma_{T,L}(x,Q^2) = \sigma_0 \sum_{f=u,d,s} \int_0^1 dz\, d\mathbf{r}\, |\Psi^f_{T,L}(e_f, m_f, z, Q^2, \mathbf{r})|^2\, \mathcal{N}^{light}(\mathbf{r}, x)$$
$$+ \sigma_0^{heavy} \sum_{f=c,b} \int_0^1 dz\, d\mathbf{r}\, |\Psi^f_{T,L}(e_f, m_f, z, Q^2, \mathbf{r})|^2\, \mathcal{N}^{heavy}(\mathbf{r}, x)\,.$$

- For consistency, we consider a variable flavor number scheme for the running of the coupling

$$\alpha_{nf}(r^2) = \frac{4\pi}{\beta_{0,nf}\, \ln\left(\frac{4C^2}{r^2\Lambda^2_{nf}}\right)} \qquad \alpha_{s,n_f-1}(r^2_\star) = \alpha_{s,n_f}(r^2_\star) \qquad r^2_\star = 4C^2/m_f^2$$

⇒ Fits with heavy quarks





- No constraints to b contribution from present data...

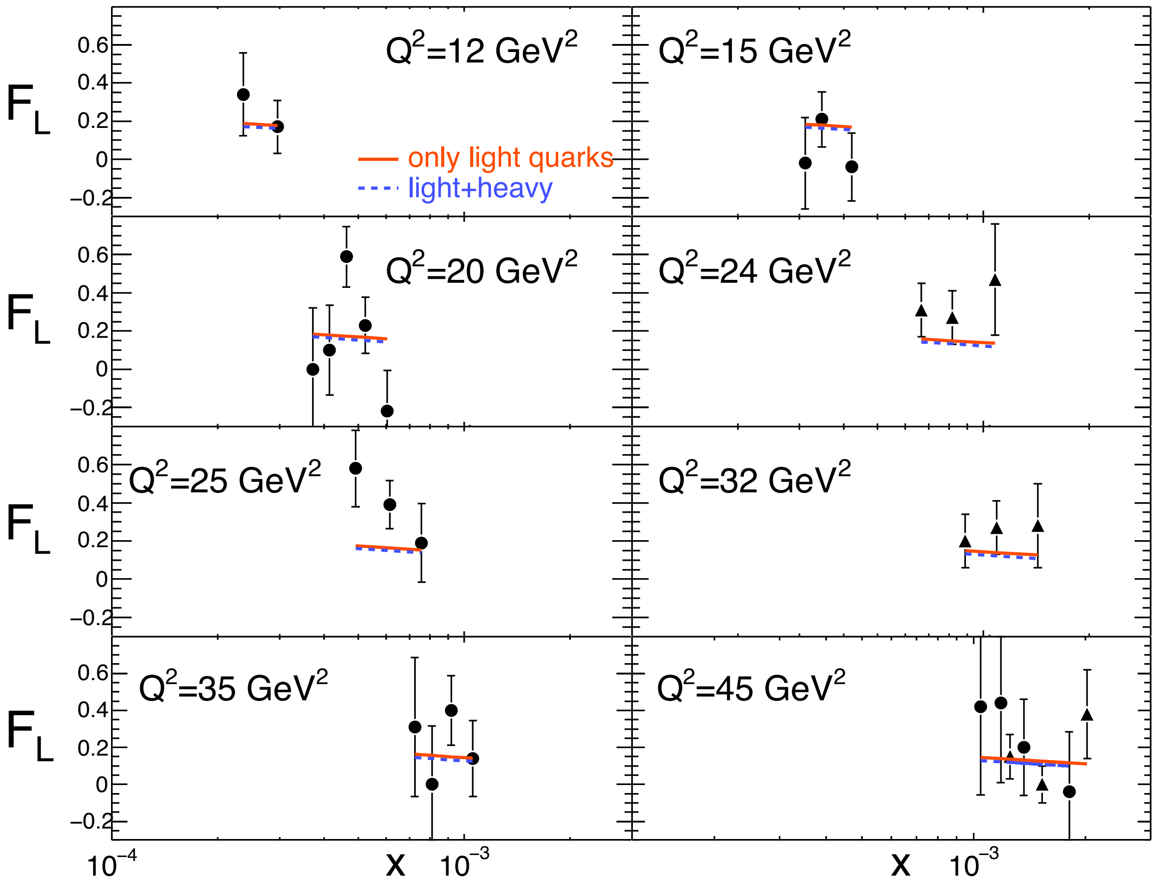
⇒ Fits with heavy quarks

	fit	$\frac{\chi^2}{d.o.f}$	Q^2_{s0}	σ_0	γ	Q^2_{s0c}	σ_{0c}	γ_c	C	m_l^2
	GBW									
a	$\alpha_{fr}=0.7$	1.269	0.2294	36.953	1.259	0.2289	18.962	0.881	4.363	fixed
a'	$\alpha_{fr}=0.7$ (Λ_{m_τ})	1.302	0.2341	36.362	1.241	0.2249	20.380	0.919	7.858	fixed
b	$\alpha_{fr}=0.7$	1.231	0.2386	35.465	1.263	0.2329	18.430	0.883	3.902	1.458E-2
c	$\alpha_{fr}=1$	1.356	0.2373	35.861	1.270	0.2360	13.717	0.789	2.442	fixed
d	$\alpha_{fr}=1$	1.221	0.2295	35.037	1.195	0.2274	20.262	0.924	3.725	1.351E-2
	MV									
e	$\alpha_{fr}=0.7$	1.395	0.1673	36.032	1.355	0.1650	18.740	1.099	3.813	fixed
f	$\alpha_{fr}=0.7$	1.244	0.1687	35.449	1.369	0.1417	19.066	1.035	4.079	1.445E-2
g	$\alpha_{fr}=1$	1.325	0.1481	40.216	1.362	0.1378	13.577	0.914	4.850	fixed
h	$\alpha_{fr}=1$	1.298	0.156	37.003	1.319	0.147	19.774	1.074	4.355	1.692E-2

- Larger transverse "size" of the light contribution $\sigma_0^{light} > \sigma_0^{charm}$
- chi^2/dof improve significantly if charm data excluded in its calculation

⇒ Fits with heavy quarks

- In both cases, i.e. only light or light+heavy quarks, a good description of FL data (not included in the fits) is obtained



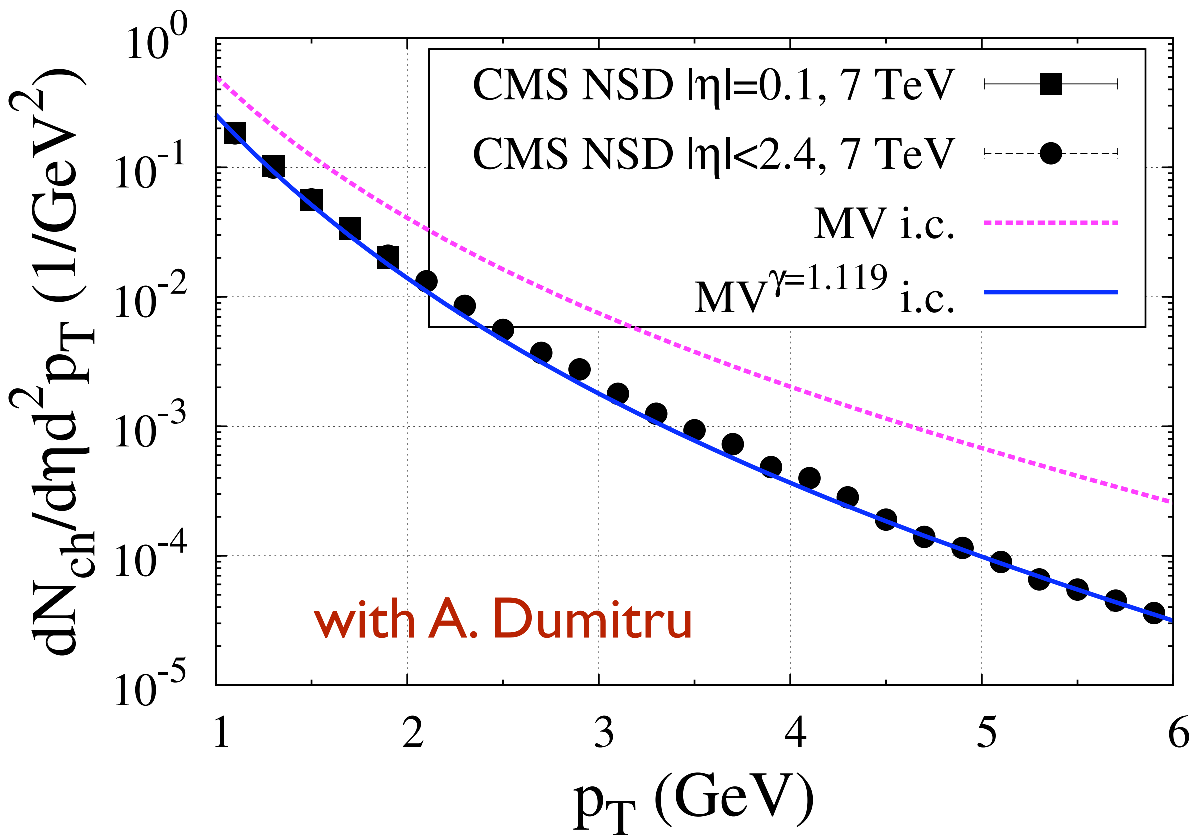
- Steeper than MV (i.e gamma>1) preferred by the fits are needed to describe the p+p spectra measured at the LHC. kt-factorization+KKP fragmentation

$$\mathcal{N}^{MV}(r, x_0 = 10^{-2}) = 1 - \exp\left[-\left(\frac{r^2\, Q_{s0}^2}{4}\right)^{\gamma} \ln\left(\frac{1}{r\,\Lambda_{QCD}}\right)\right] \qquad \gamma = 1.119$$

$$\frac{d\sigma^{A+B\to g}}{dy\, d^2p_t\, d^2R} = \kappa\, \frac{2}{C_F}\frac{1}{p_t^2} \int^{p_t} \frac{d^2k_t}{4} \int d^2b\, \alpha_s(Q)\, \varphi(\frac{|p_t + k_t|}{2}, x_1; b)\, \varphi(\frac{|p_t - k_t|}{2}, x_2; R - b)$$

unintegrated gluon distributions

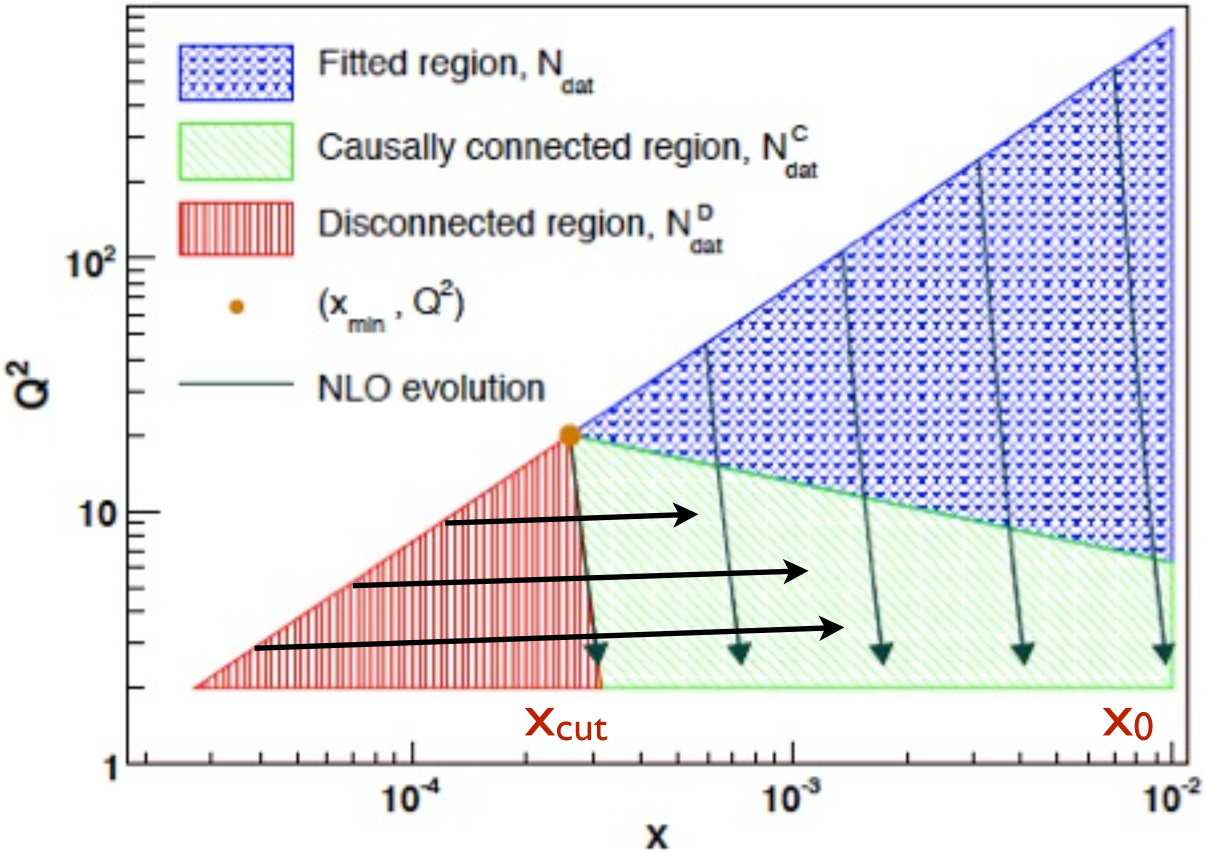
$$\varphi(k, x, b) = \frac{C_F}{\alpha_s(k)\,(2\pi)^3} \int d^2\mathbf{r}\; e^{-i\mathbf{k}\cdot\mathbf{r}}\, \nabla_{\mathbf{r}}^2 \mathcal{N}_G(r, Y = \ln(x_0/x), b)$$



⇒ Delineating the saturation boundary (G Milhano, P. Quiroga and J Rojo):

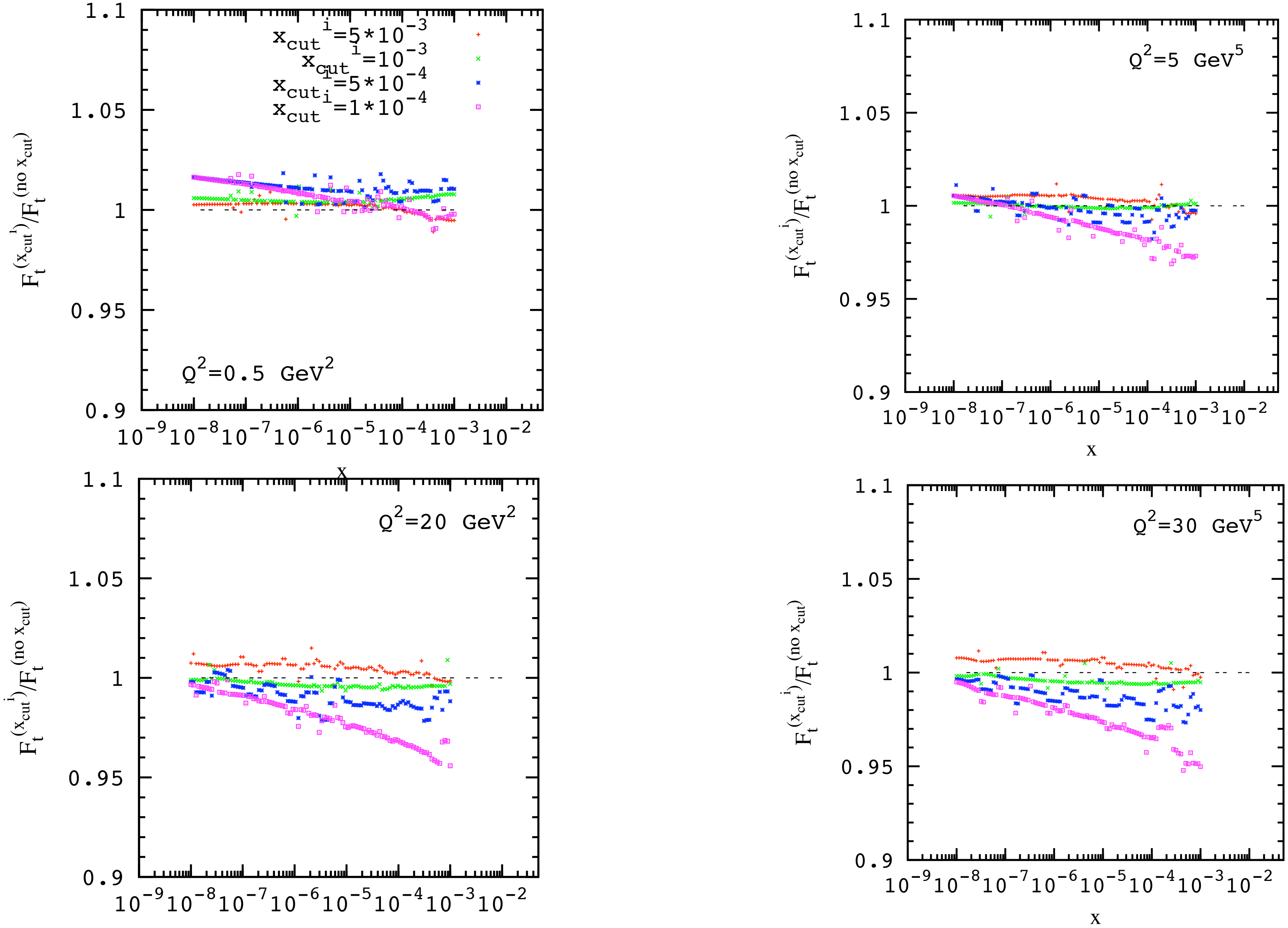
- NLO DGLAP analysis exhibit deviations after systematic exclusion of low-Q^2 regions ("saturation cuts") from the fits (Caola, Forte, Rojo)

- Analogous exercise with rcBK:
  - Systematically exclude high-x regions from the fits ($x>x_{cut}>x_0=10^{-2}$)
  - Compare with fits including the region ($x>x_{cut}=10^{-2}$)



⇒ Delineating the saturation boundary (G Milhano, P. Quiroga and J Rojo):

- Small deviations found. They indicate that other relevant physics (DGLAP, NP...?) not included in our rcBK approach is relevant in the excluded region. They increase with
  - decreasing x_{cut}
  - increasing Q^2



Summary

- Running coupling BK evolution successfully describes new combined H1+ZEUS data on reduced cross sections at small-x
- Fit parameters are stable after the inclusion of the new data
- Charm contribution to the cross section can be accounted for, albeit allowing a smaller radius for the charm distribution in the proton than for light ones
- Steeper than MV initial conditions preferred by the fits also provide a better description of p+p yields measured at the LHC
- Systematic exploration of the saturation boundary ongoing
- Next: analogous global fits for nuclear data, include NLO photon impact factor, realistic b-dependence...

Parametrizations of the proton-dipole amplityde available at
http://www-fp.usc.es/phenom/software.html

Thanks!

BACK UP SLIDES

- The dominant contribution to the evolution is given by the running term
- Balitsky's separation scheme minimizes the role of the subtraction term w.r.t. to KW's one

$$\frac{\partial S}{\partial Y} = \mathcal{R}\left[S\right] - \mathcal{S}\left[S\right]$$

$$\frac{\mathcal{S}\left[S\right]}{\mathcal{R}\left[S\right]}$$